PREDICTION OF VEHICLE MOBILITY ON LARGE-SCALE SOFT-SOIL TERRAIN MAPS USING PHYSICS-BASED SIMULATION

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GVSETS

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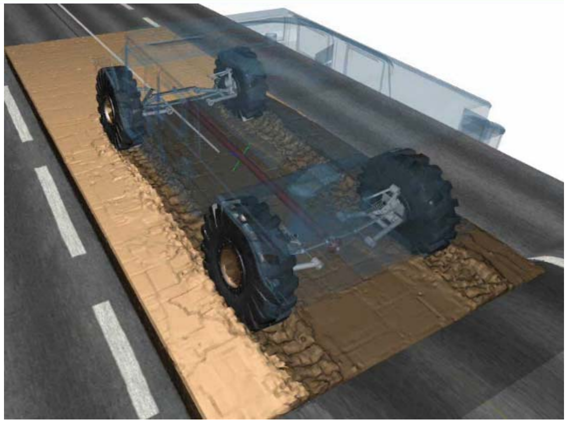
Motivation/NRMM



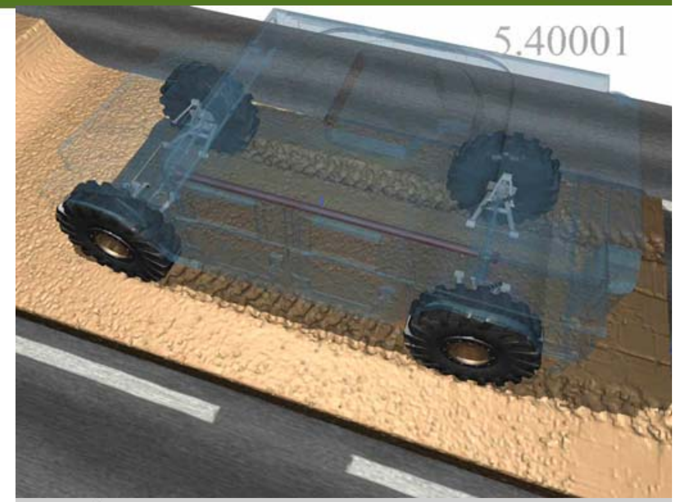
- Mobility measures include:
  - Speed-made-good.
  - Fuel consumption.
  - Vibration power transmitted to occupants/payloads.
- Currently Army uses NRMM (developed in 1970's) to predict speed-made-good maps.
- NRMM is based on empirical relations and considers the following terrain variables:
  - Soil cone index (CI); surface cover (normal, water or snow); grade (uphill, downhill, and side); surface roughness; mound/trench obstacle size and spacing; tree/vegetation stem size and spacing; visibility.
- Empirical relations tuned using 1960's to 1980's military vehicles.
- NRMM may not be accurate for new military vehicles: oversized wheels/tracks; small robotic vehicles; airless tires; belt-type tracks; vehicles with independent suspension or control technologies such as ABS, TCS, ESC, etc..
- Tuning the empirical relations is very expensive and time consuming.

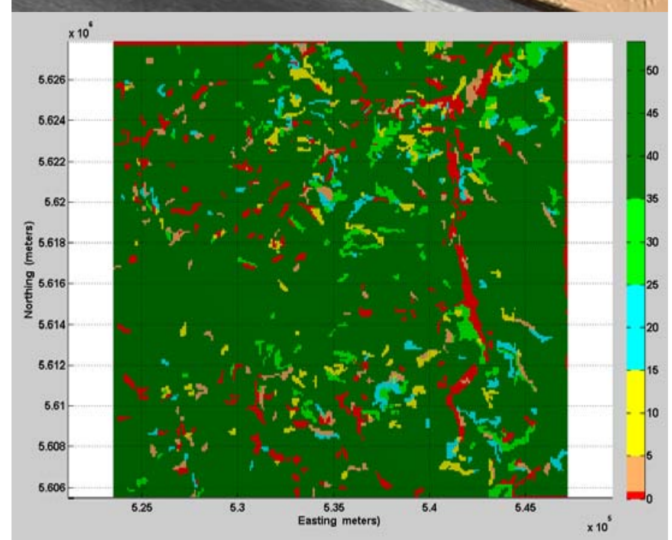
Objectives

- Develop a **high-fidelity physics-based** technique to accurately and reliably predict vehicle mobility maps over large-scale off-road terrain maps.

- The focus of the paper is on only two terrain variables:
  - Soil shear strength measured by the Cone Index (CI).
  - Terrain uphill grade.

- Rest of the terrain parameters will be considered in future work.

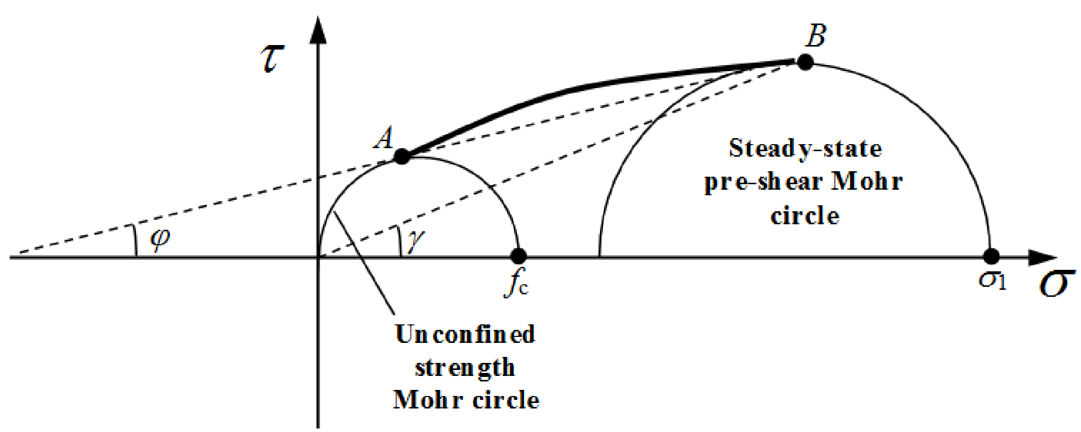




Terrain map (22 km x 22 km) colored by speed-made-good in mph

Soft Soils

- Soft soils can be divided into: cohesive and non-cohesive.
- This paper focuses on cohesive soils.
- Cohesive soils modeling challenges:
  - Bulk density & shear strength increase with normal compressive stress.
  - Bulk density & shear strength values are maintained after removal of the normal compressive stress (consolidation/memory effect).
  - Bulk density & shear strength values decrease when the soil is subjected to normal tensile stress (relaxation effect).
  - Nonlinear elastic, damping, viscous, and friction response.



Physics-Based Soil Models

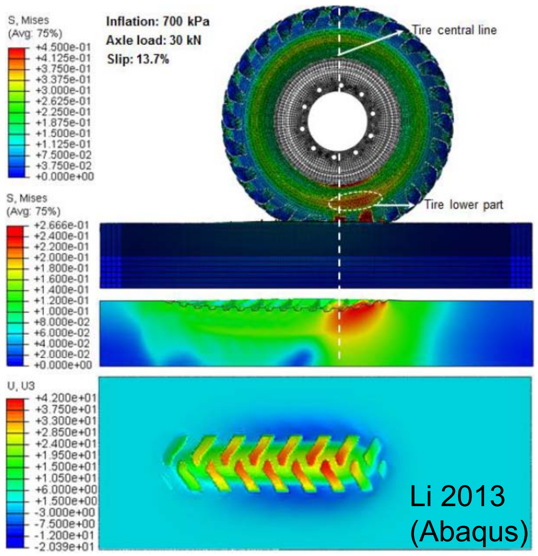
Physics-based models for soil include:

- Height-field models.
- Finite Element models.
- Particle-based models.
  - Smoothed Particle Hydrodynamics (SPH)
  - Material Point Method (MPM)
  - Discrete Element Method (DEM)

- Height-field models
  - Calculate normal & tangential forces between a tire/track shoe and a plastically deformable soil surface based on sinkage and relative normal & tangential velocities.
  - Implemented in most commercial multibody dynamics software.
  - Advantages: Fast.
  - Disadvantages:
    - Bias in vertical direction.
    - Difficulty with long and side sloped terrains.
    - Inability to correctly account for the state of 3D flow/deformation/stress in the soil.
    - Ruts, heaps, and soil separation/reattachment not accurately modeled.
    - Accuracy range limited to small-moderate soil deformation.

Physics-Based Soil Models

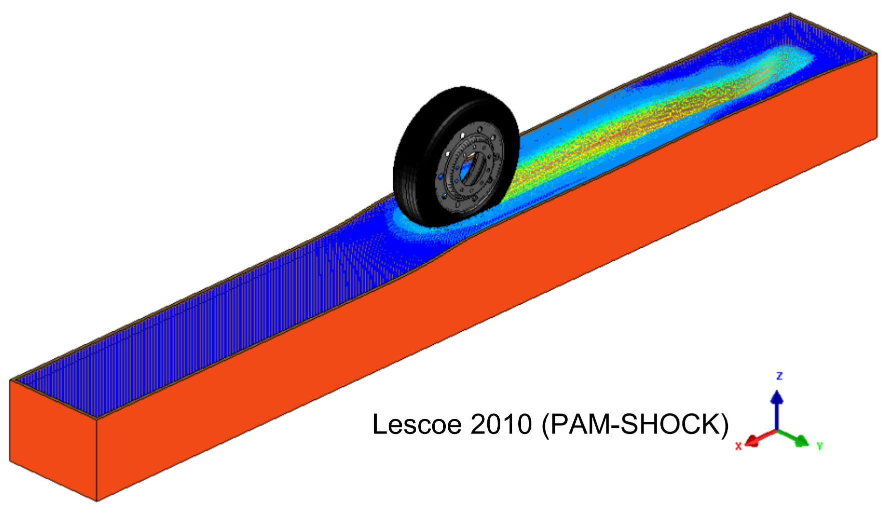
- Finite element models
  - Advantages
    - Element size can be spatially varied.
  - Disadvantages
    - Soil constitutive models (eg. Drucker-Prager-Cap) cannot automatically account for flow.
    - Constitutive material model which accounts for: flow, fracture, plasticity, friction, and cohesion, and their dependence on stress/stress history is an open research problem.
    - ALE can be used to model flow. However, special treatment is needed to avoid small node mass.
    - Inability to capture soil separation/reattachment without special techniques such as VOF and level-set.
    - Difficult to capture large deformation effects (ruts & heaps) since remeshing is needed.
    - Remeshing reduces solution accuracy since the solution fields must be re-interpolated to the new mesh.
    - Remeshing is computationally expensive.



Li 2013 (Abaqus)

Physics-Based Soil Models

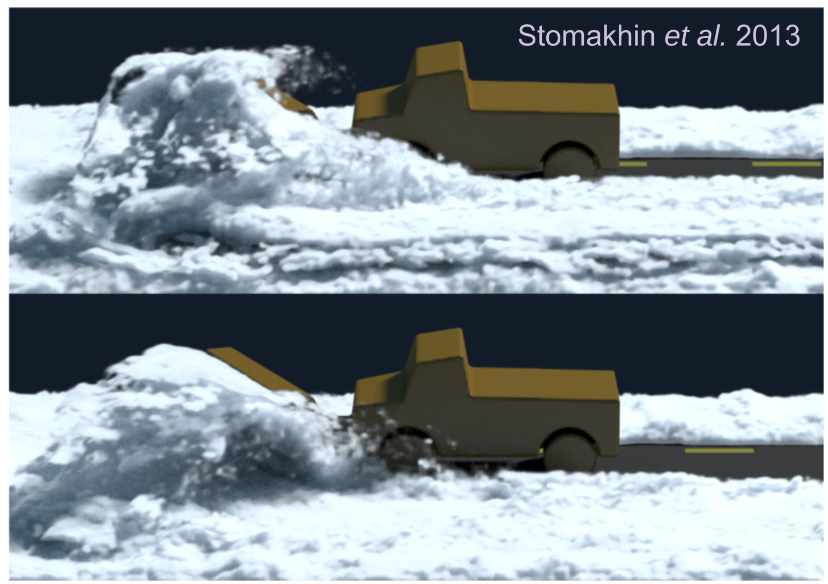
- Smooth particle hydrodynamics (SPH)
  - The continuum mechanics governing equations are discretized for each particle using a kernel smoothing function used to evaluate (interpolate) each particle properties and fluxes using neighboring particles.
  - Advantages
    - Can easily account for large material deformation, flow, and separation/reattachment.
  - Disadvantages
    - Large number of particles are needed → Computationally expensive.
    - Rely on a continuum mechanics formulation, and therefore, requires a continuum mechanics cohesive soil constitutive material model.



Lescoe 2010 (PAM-SHOCK)

Physics-Based Soil Models

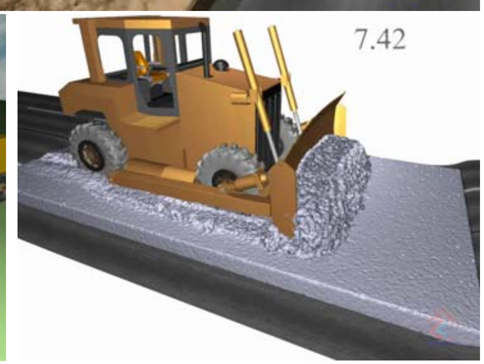
- Material-Point-Method (MPM).
  - A Cartesian grid is used along with the particles to find neighboring particles as well as to discretize and solve the continuum mechanics governing equations.
  - Advantages
    - Can easily account for large material deformation, flow, and separation/reattachment.
  - Disadvantages
    - Large number of particles are needed → Computationally expensive.
    - Rely on a continuum mechanics formulation, and therefore, requires a continuum mechanics cohesive soil constitutive material model.



Physics-Based Soil Models

- Discrete Element Method (DEM)
  - Material behavior modeled using inter-particle forces which include normal (elastic, damping, and cohesive) and tangential (viscous and friction) contact forces.
  - Advantages
    - Can easily account for large material deformation, flow, & separation/reattachment.
    - Closer the physics of actual soil particles. → easier to develop inter-particle force models.
  - Disadvantages
    - Large number of particles are needed → Computationally expensive.
  - ***Chosen for modeling soft soil in this study.***

Wasfy *et al.* 2013-2015



Current Approach

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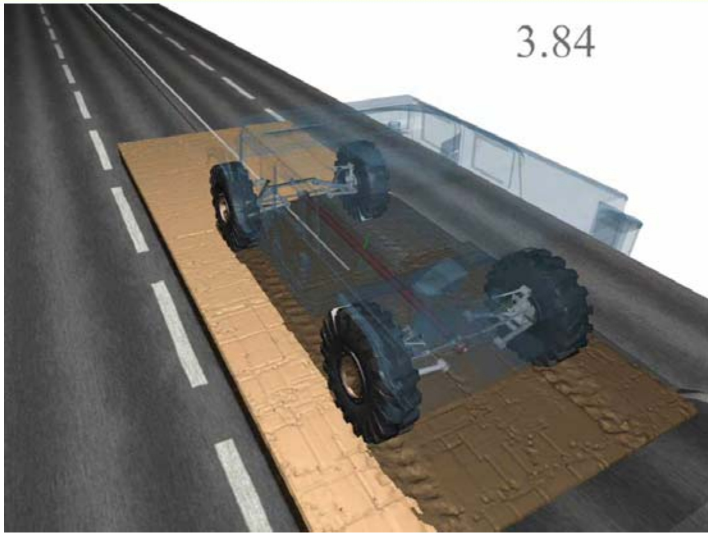
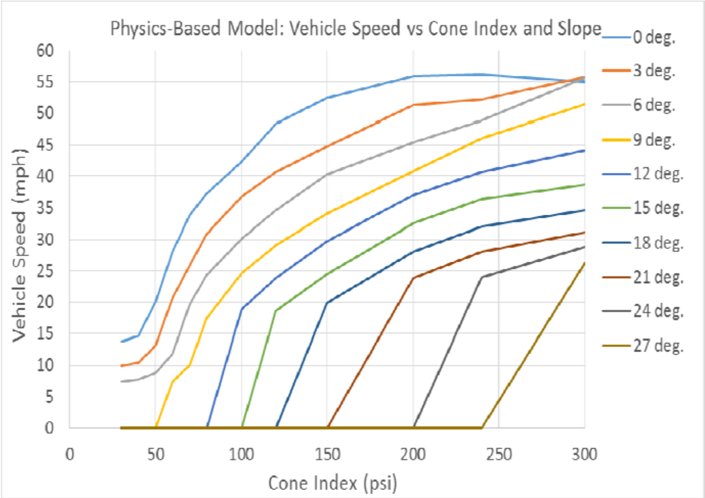
- **One-solver approach**: DEM and multibody dynamics are seamlessly integrated into one explicit time-integration solver.
  - **General cohesive soil material DEM model**.
  - **High-fidelity multibody dynamics model** of a typical 4x4 military vehicle.
  - The cone index is calibrated to the DEM soil model using a **simulation of a cone penetrometer experiment.**
  - To enable predicting high vehicle speeds (up to 60 mph), a **moving soil patch strategy** is used.

- **An HPC-based DOE procedure** is used to generate the terrain mobility maps, considering two terrain variables: Cone index and up-hill slope.





MBD/DEM Formulation

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- Semi-discrete translational and rotational equations of motion:

$$M_K \ddot{x}^t_{Ki} = {F_s}^t_{Ki} + {F_a}^t_{Ki} \qquad I_{Kij}\ddot{\theta}^t_{Kj} = {T_s}^t_{Ki} + {T_a}^t_{Ki} - \left(\dot{\theta}^t_{Ki} \times (I_{Kij}\dot{\theta}^t_{Kj})\right)_{Ki}$$

- Lumped mass and inertia matrices are used.
- Rotational equations of motion written in a body (material) frame.
- The equations of motion are integrated using a semi-explicit parallel solution procedure that uses the trapezoidal-integration rule.

$$\dot{x}^t_{Kj} = \dot{x}^{t-\Delta t}_{Kj} + 0.5\,\Delta t\,(\ddot{x}^t_{Kj} + \ddot{x}^{t-\Delta t}_{Kj}) \qquad \dot{\theta}^t_{Kj} = \dot{\theta}^{t-\Delta t}_{Kj} + 0.5\,\Delta t\,(\ddot{\theta}^t_{Kj} + \ddot{\theta}^{t-\Delta t}_{Kj})$$

$$x^t_{Kj} = x^{t-\Delta t}_{Kj} + 0.5\,\Delta t\,(\dot{x}^t_{Kj} + \dot{x}^{t-\Delta t}_{Kj}) \qquad \Delta\theta^t_{Kj} = 0.5\,\Delta t\,(\dot{\theta}^t_{Kj} + \dot{\theta}^{t-\Delta t}_{Kj})$$

- The incremental rotations are added to the total body rotation matrix.

$$R^t_K = R^{t-\Delta t}_K\, R(\Delta\theta^t_{Ki})$$

- Translational DOFs referenced to the global inertial reference frame.
- Rigid-body rotations referenced to a body-fixed frame.

Joints

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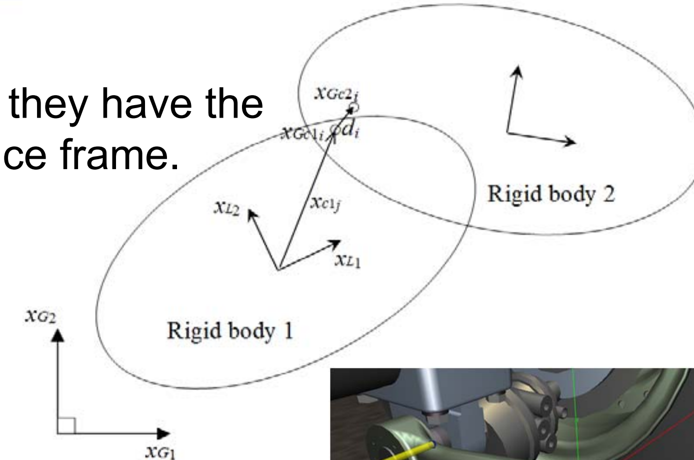
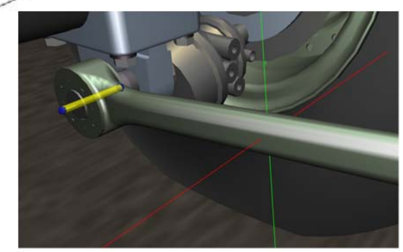
- ***Penalty formulation is used for all joints.***
- ***Spherical Joint***: Constrains 2 points on 2 bodies such that they have the same translational coordinates relative to the global reference frame.



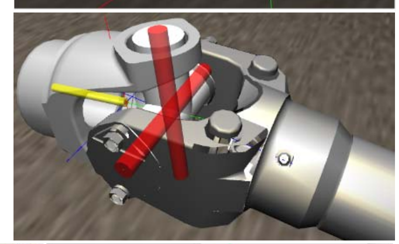
$$F_P = k_P\, d + c_P\; d_i \dot{d}_i / d$$

$$d_i = X_{c1_i}^t - X_{c2_i}^t \qquad \dot{d}_i = \dot{X}_{c1_i}^t - \dot{X}_{c2_i}^t$$

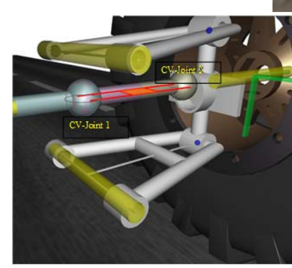
$$d = \sqrt{d_1^{\,2} + d_2^{\,2} + d_3^{\,2}} \qquad F_{P_i} = F_P\, d_i / d$$

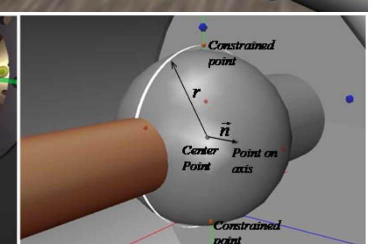


- ***Revolute joint*** 2 spherical joints along a line
- ***Universal joint*** 2 perpendicular revolute joints



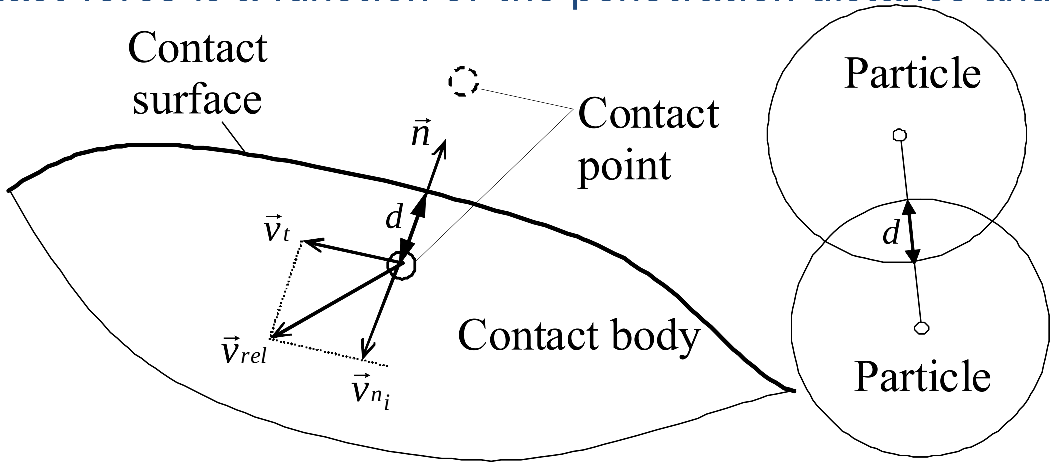
- ***Bracket joint*** 4 non-coincident spherical joints
- ***Cylindrical Joint*** 2 points restricted to move on a line
- ***Prismatic joint*** 2 parallel cylindrical joints
- ***CV joint*** 2 perpendicular cylindrical circular-path joints with 2 points restricted to move along each path





Penalty Contact Model

- The normal contact force is a function of the penetration distance and penetration velocity.



$$F_{c_i} = F_{n_i} + F_{t_i}$$

$$F_{n_i} = n_i \left| F_n \right|$$

$$\left| F_n \right| = F_{adhesion} + F_{repulsion} + F_{damping}$$

$$F_{repulsion} = f(d) = k_n d$$

$$F_{damping} = g(d, \dot{d}) = \begin{cases} c_n \dot{d} & \dot{d} \geq 0 \\ s_n c_n \dot{d} & \dot{d} < 0 \end{cases}$$

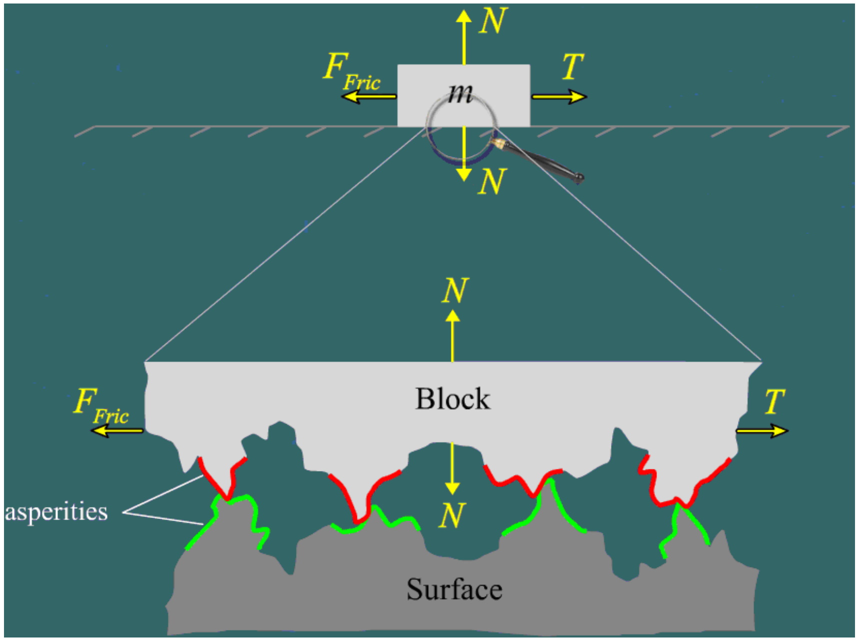
$$F_{t_i} = t_i \left| F_t \right|$$

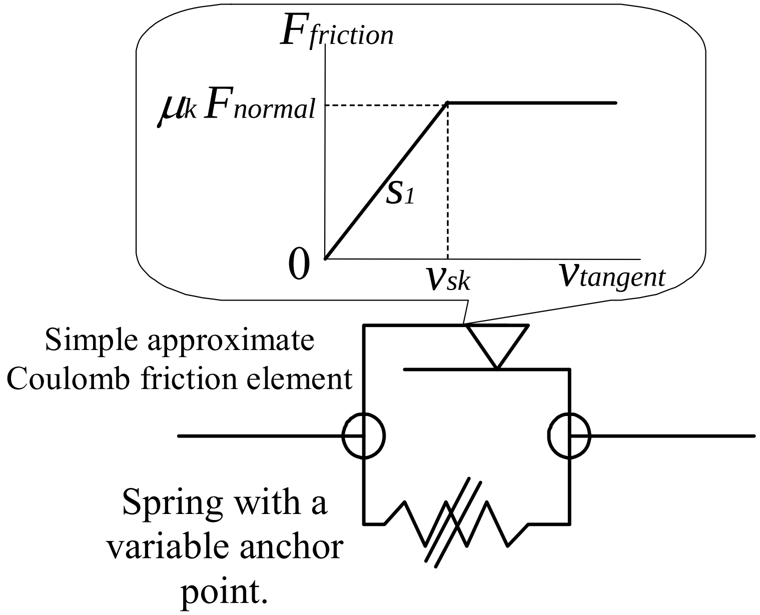
$$\left| F_t \right| = F_{viscous} + F_{friction}$$

$$F_{viscous} = c_t \left| v_t \right|$$

$$|F_t| = F_{viscous} + F_{friction}$$

- **Asperity friction model (approximate Coulomb friction model).**





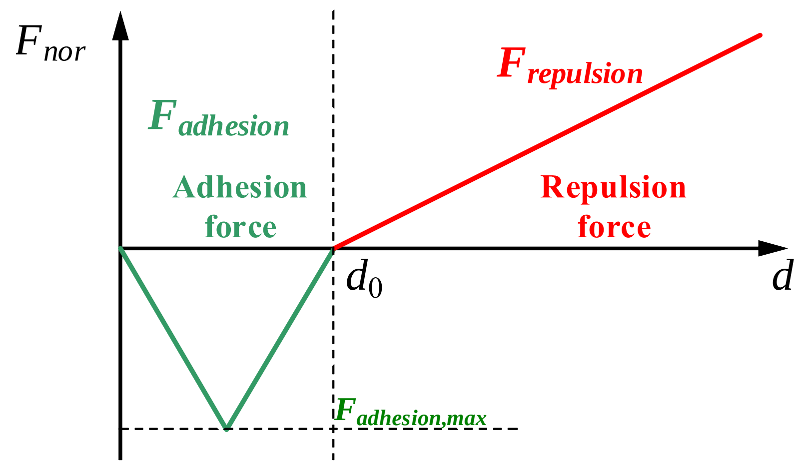
DEM Cohesive Soil Model (1/2)

- Spherical point particles (no rotational DOFs).
- The contact force model includes:
  - **Normal adhesion and repulsion forces** as a function of penetration (d).

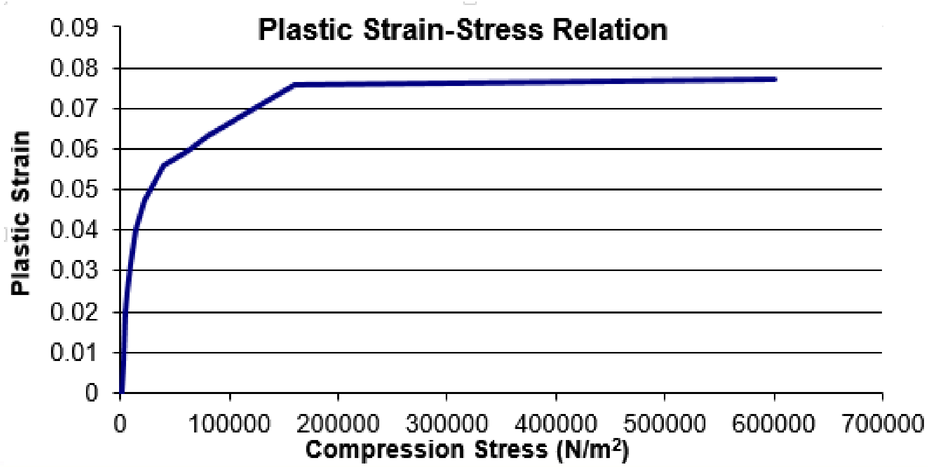
$$|F_n| = F_{adhesion} + F_{repulsion} + F_{damping}$$

  - **Tangential forces:**

$$|F_t| = F_{viscous} + F_{friction}$$



  - **Plastic deformation specified as a function of repulsion (compression) force**.



DEM Cohesive Soil Model (2/2)

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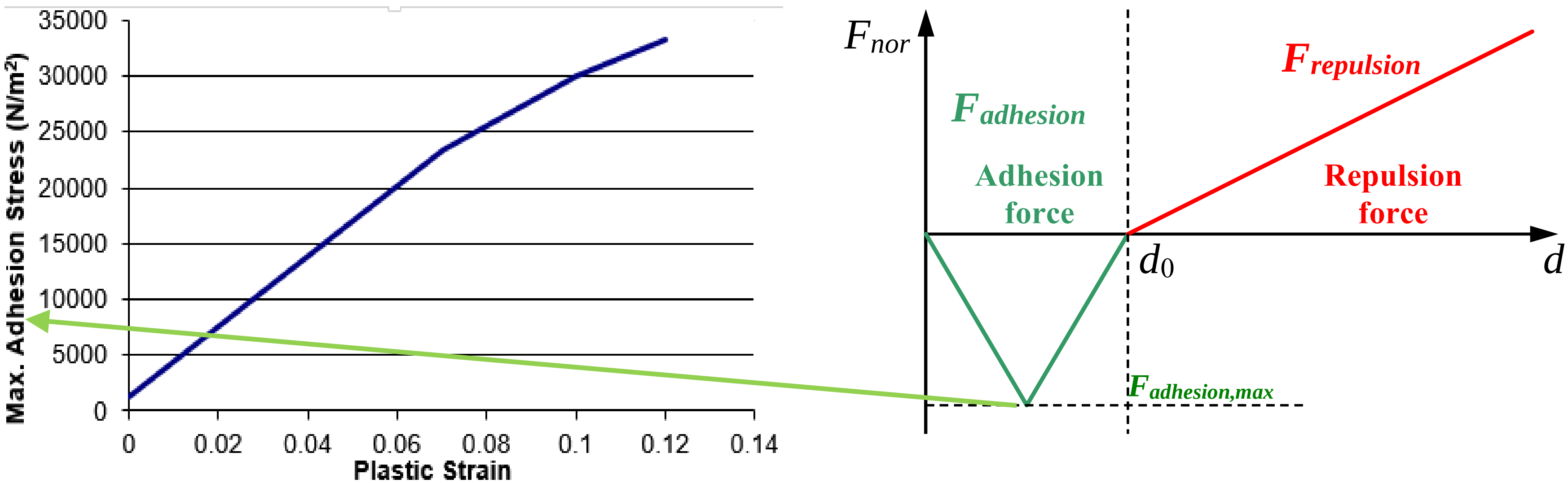
- **Maximum adhesion force is a function of plastic deformation.**



Cohesion factor f used to scale the above graph.

- **Time relaxation:** accounts for reduction of soil cohesive strength and soil bulk density when soil is in subjected to tension.

$$\delta_{plastic} = \delta_{plastic} - \begin{cases} 0 & F_{repulsion,\max} \geq F_{adhesion,\max} \\ V_{relax} \times \Delta t & F_{repulsion,\max} < F_{adhesion,\max} \end{cases}$$

Cone Penetrometer Experiment (1/2)

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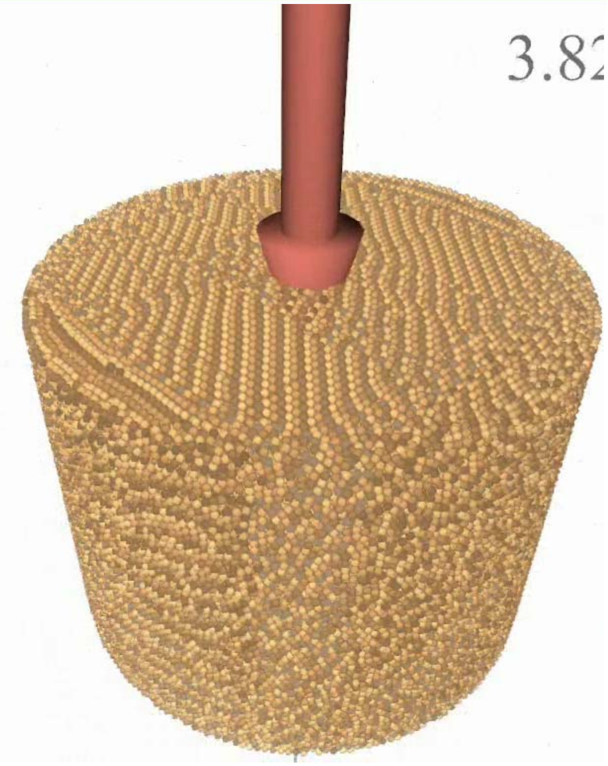
- MBD/FE model of standard cone penetrometer used to calibrate the cone index (CI) used in NRMM with the parameters of the DEM soil material model.
- The CI is tuned by varying two DEM parameters:
  - Cohesion factor: f
  - Friction coefficient: μ

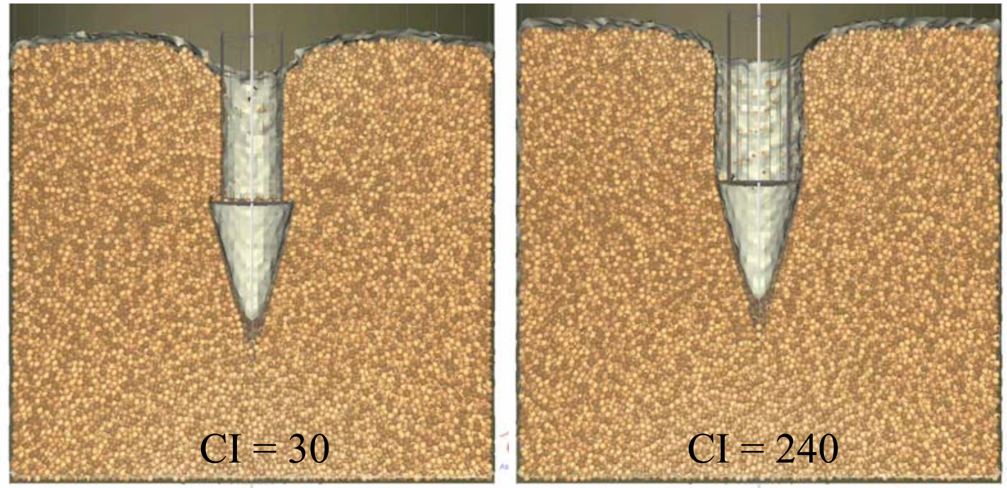


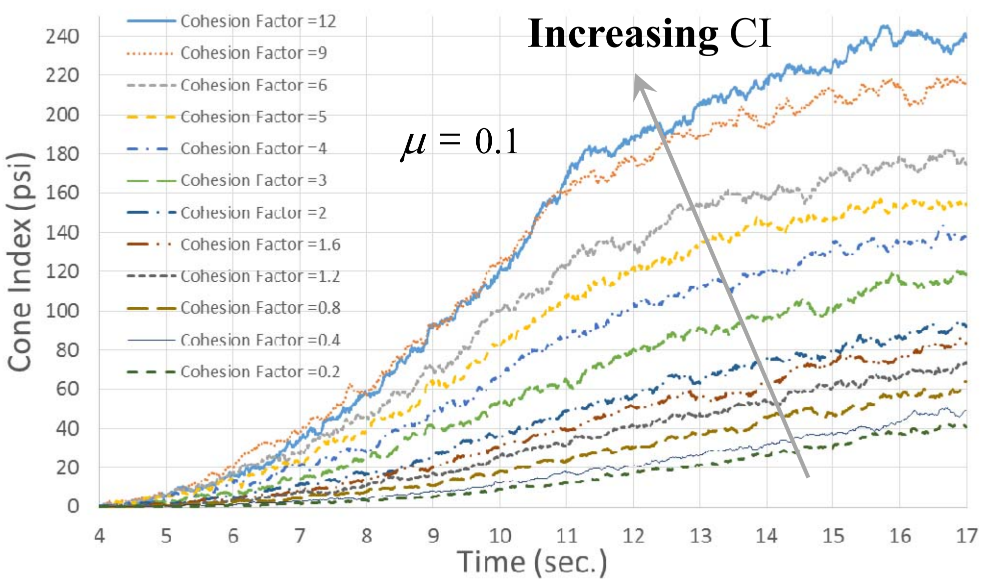
Unstressed (unconsolidated) particle diameter	0.03 m
Particle mass density	1800 kg/m^3
Inter-particle friction coefficient	0.1
Particle to tire/cone penetrometer friction coefficient	0.5
Inter-particle viscosity	0
Inter-particle damping per unit area	2.1×10^4 N/m^3/s
Particle stiffness (slope of repulsion stress versus penetration strain in Figure 7)	4.42×10^7 N/m^2
Plastic strain versus compressive stress	Slide Figure
Nominal maximum adhesion stress versus plastic strain curve	Slide Figure
Plastic relaxation speed	0.045 m/s
Total number of DEM particles	300,000

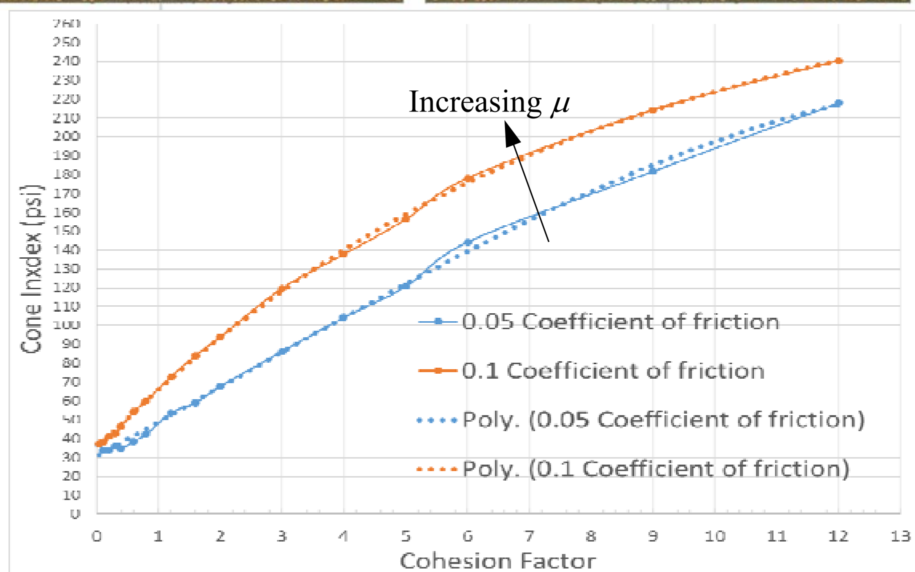
Cylindrical container diameter	2 m
Consolidating lid pressure	33.3 kPa
Cone penetrometer base diameter	0.375 m
Cone penetrometer length	0.7 m
Cone penetrometer cone angle	30º
Penetrometer speed	0.1 m/s
Δt	1.5×10^{-5} s

Cone Penetrometer Experiment (2/2)

- Fix μ at 0.1 and vary f between 0.2 to 12 to tune to the value of CI.
- 3[rd] order polynomial used to map f to CI.

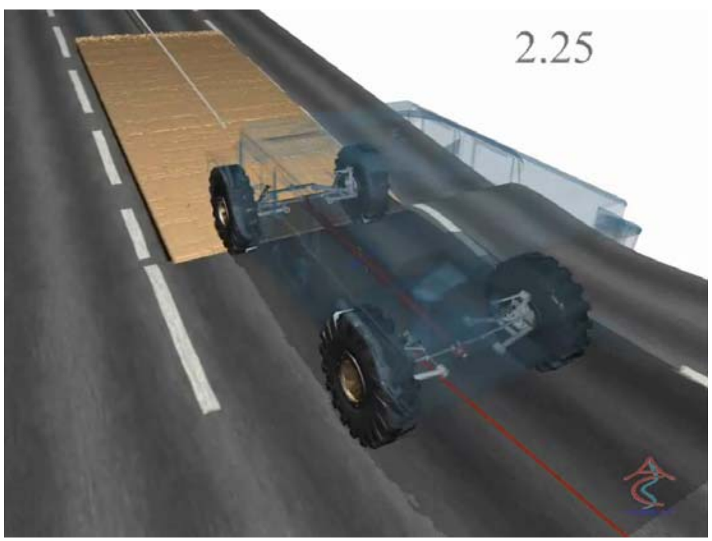


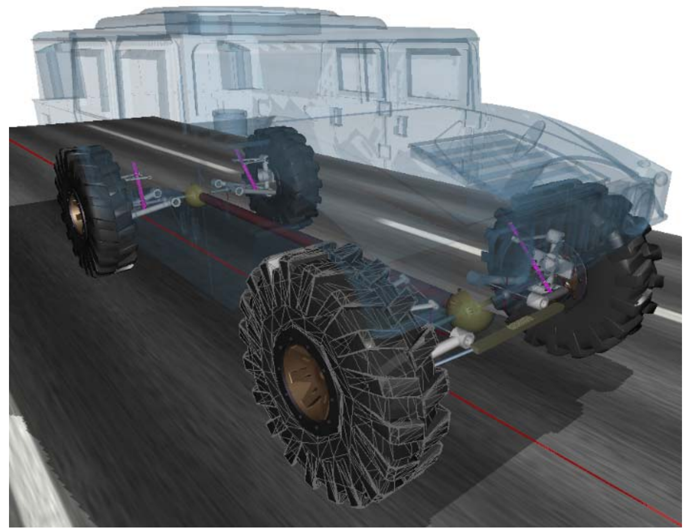




Vehicle-Soil Model (1/3)

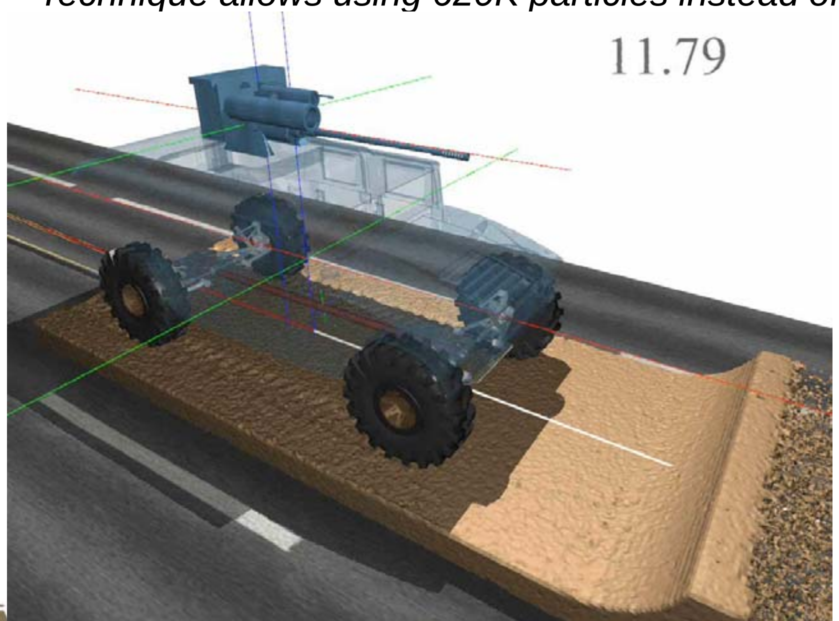
- HMMWV driving over a soft cohesive soil.
  - Two soil parameters: CI and positive long grade.
- Vehicle model
  - Rotational actuator for modeling the engine (torque limited by engine characteristics).
  - Total sprung mass = 4430 kg.
  - Wheel mass = 50 kg.
  - Contact between the tires – ground: polygonal tire contact surface (6662 triangles).

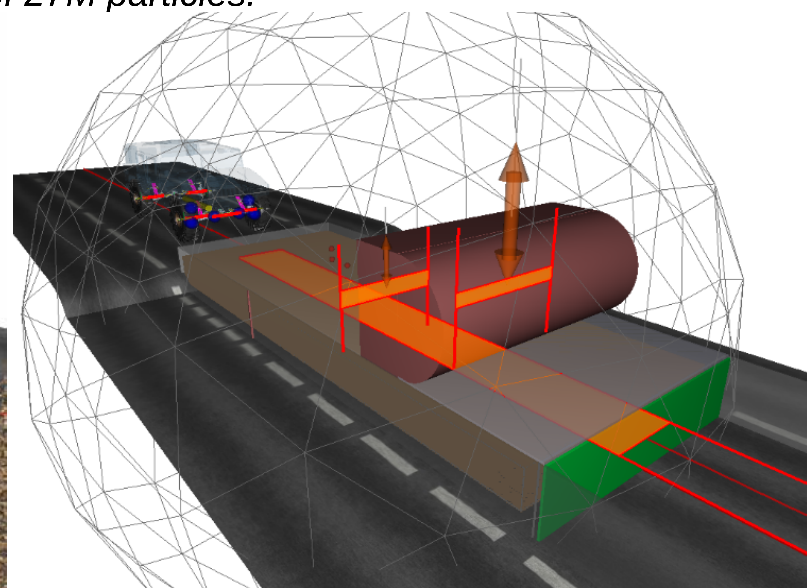




Vehicle-Soil Model (2/3)

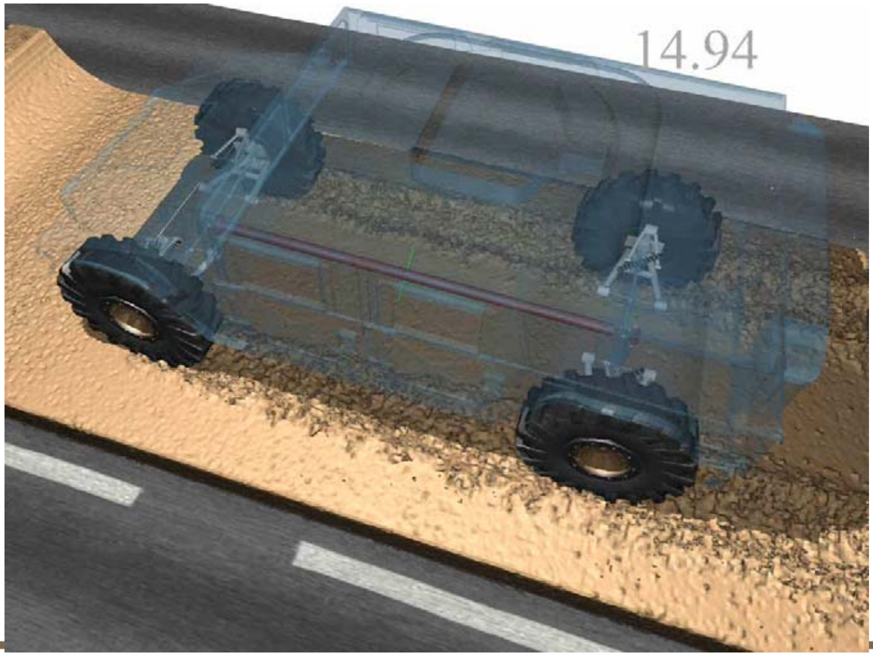
- 620,000 DEM particles.
- Undeformed particle diameter = 3 cm.
- Soil particles inside bounding box: 9.3 m long, 3.5 m wide, 0.9 m high.
- Soil is compressed using a flat lid. Pressure = 33.3 kPa.
- Lid is removed after consolidated soil settles to a height ≈ 0.4 m.
- Moving soil patch technique:
  - **Components:** Rectangular particle emitter, leveling cylinder/plate, and bounding sphere.
  - X-coordinate of center of bounding sphere is moved with the X-coordinate of center of vehicle.
  - When a particle goes outside the bounding sphere, it is deactivated and then reemitted.
  - *Technique allows using 620K particles instead of 27M particles.*





Vehicle-Soil Model (3/3)

- Terrain and soil patch are set to the desired grade.
- Simulation starts by leveling and consolidating the soil using the flat lid.
- Leveling cylinder and plate are lowered to the initial height of the soil (about 0.4 m).
- Vehicle is commanded to accelerate at 1 m/s^2 from rest to a maximum speed of 25 m/s (56 mph) in 25 sec.
- Soil and grade resistances cause the vehicle speed to level off below the commanded maximum speed, at which point the engine is applying the maximum available torque.
- Total simulation time = 40 sec; Time step = 1.5×10^{-5} s
- Steady-state maximum vehicle speed is the “speed-made-good.”



Vehicle Mobility DOE Procedure

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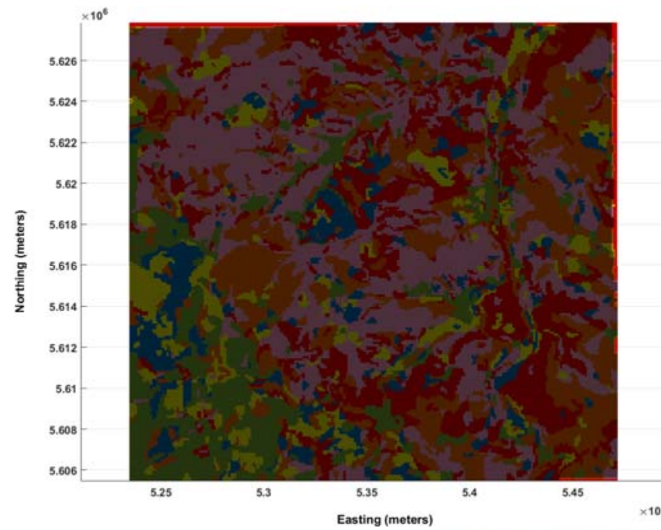
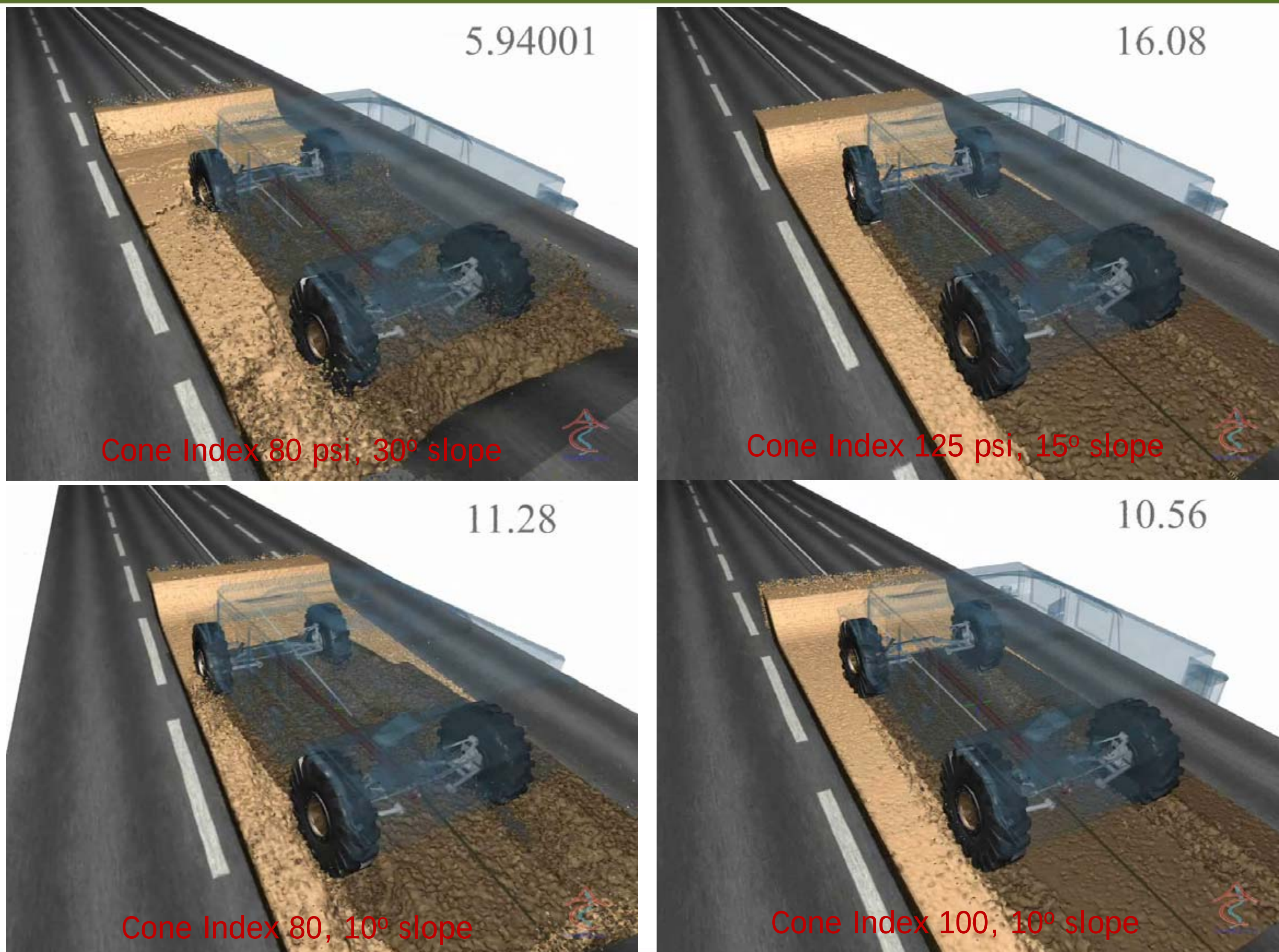
- Terrain map (22 x 22 km) is divided into grid cells of the same size as the vehicle (20 × 20 m).
- For each grid cell **slope** and **CI** are found.
- Range of slopes and CIs for the entire terrain map are found.
- Positive slope range of the terrain map is discretized into a certain number of values (*G*). The CI range is discretized into a certain number of values (*C*).
- A vehicle mobility simulation is performed for each of the *G*×*C* combination of slope and CIs. All the combinations are run in parallel on individual HPC nodes.
- For each combination, steady-state vehicle mobility measures are calculated.
- The mobility measure values for each terrain grid cell are interpolated from the calculated values.
- A map of the mobility measure over the entire terrain map is generated by coloring each grid cell using the mobility measure (such as the speed-made-good).



Simulation Results (1/4)



Simulation Results (2/4)

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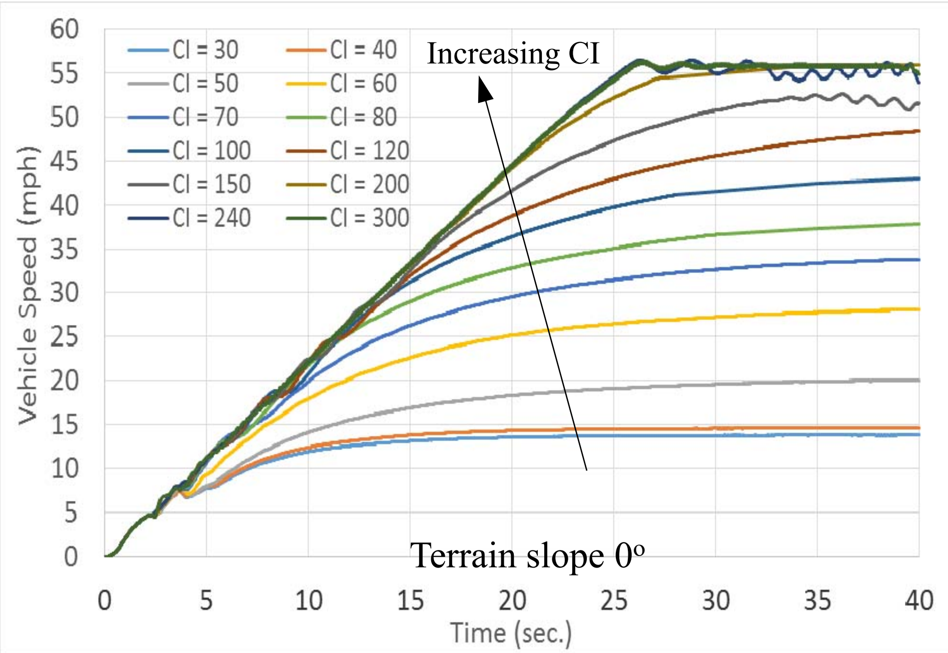
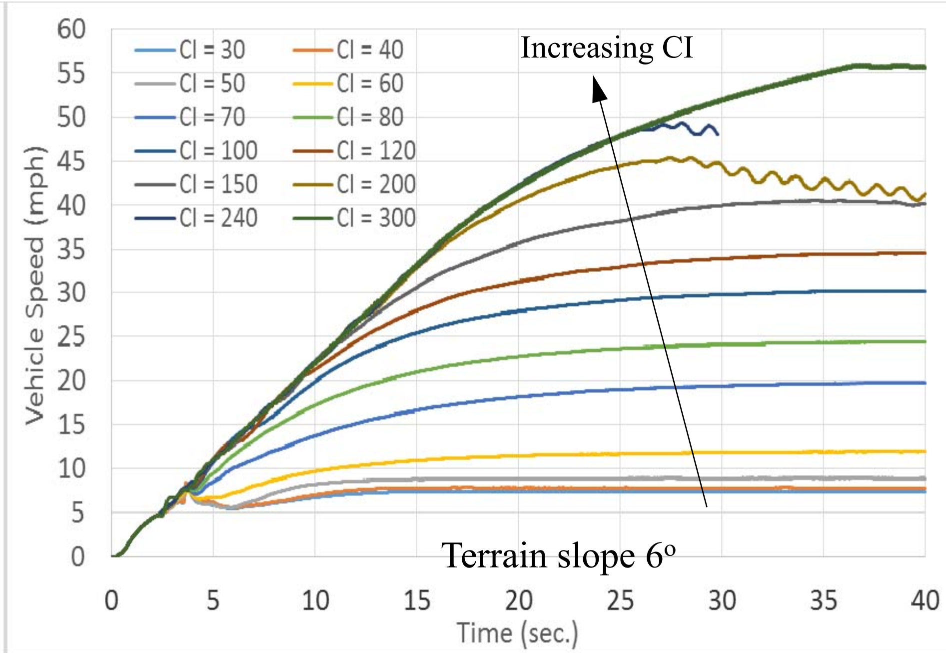
- Time-history of vehicle speed for different soil CI and terrain slopes.

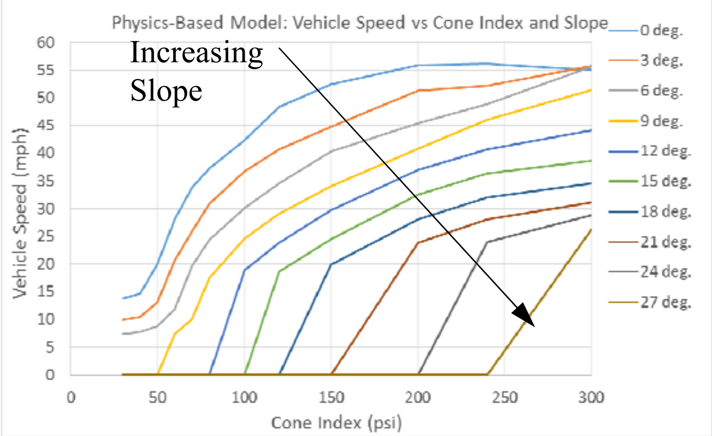


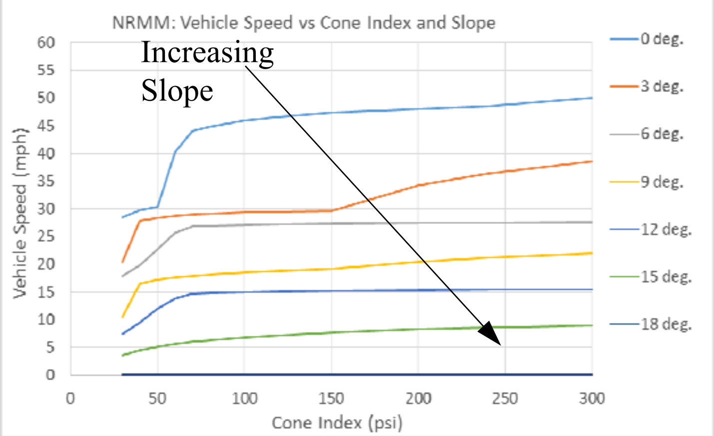


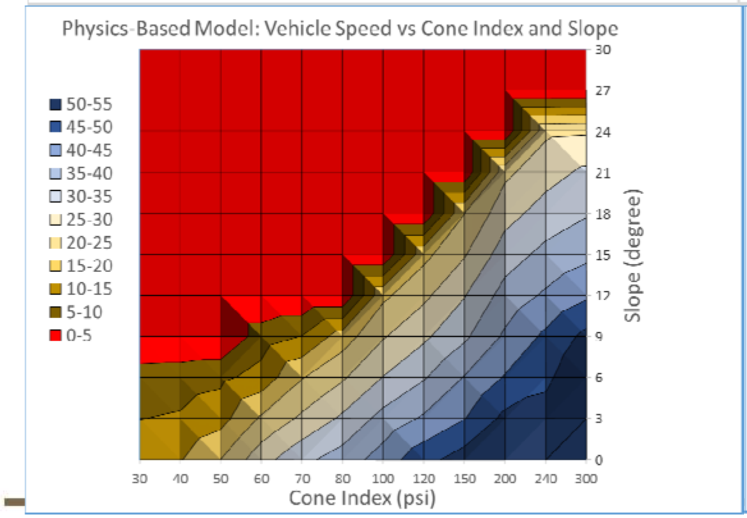
- As cone-index increases vehicle speed increases for all slopes.
- As slope increases vehicle speed decreases.

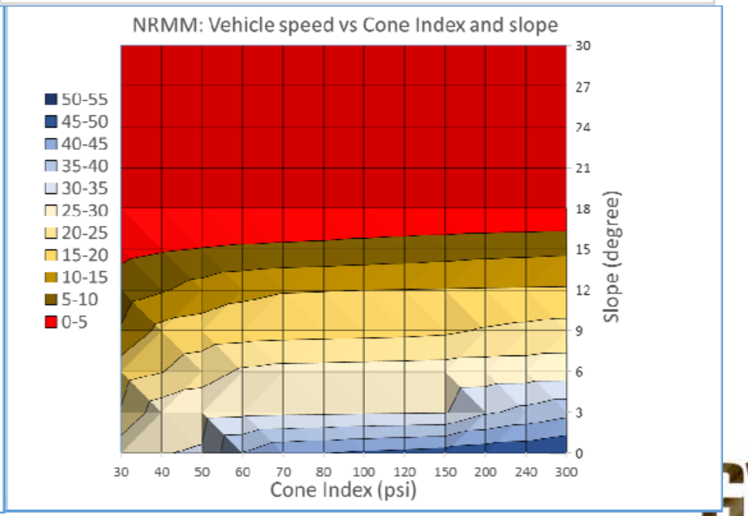
Simulation Results (3/4)

- Vehicle speed-made-good as a function of CI and terrain slope.
  - For the current physics-based model, as expected: vehicle speed is proportional to CI and inversely proportional to slope.
- The results of the current model and NRMM are different.





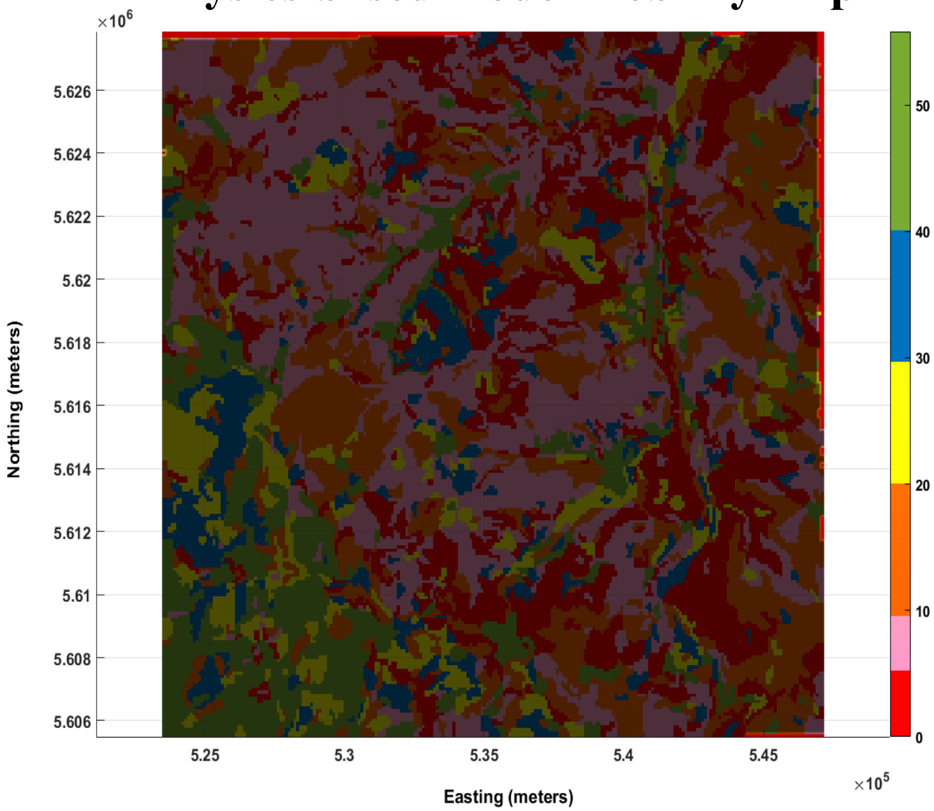




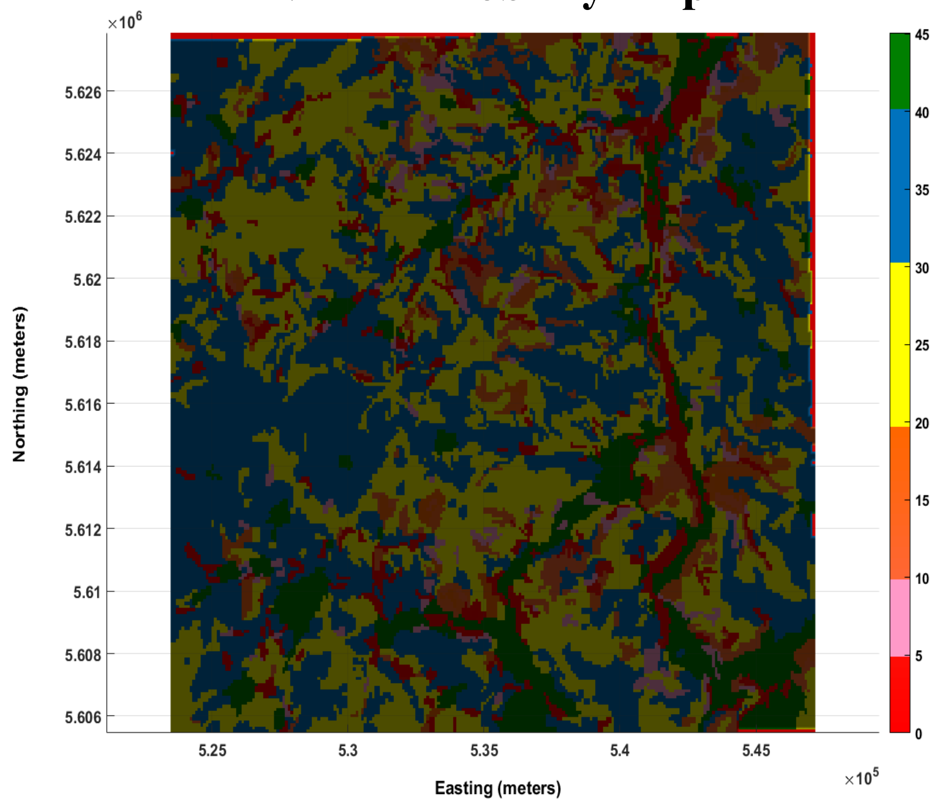
Simulation Results (4/4)

- Comparison of mobility maps generated by the current physics-based model and NRMM

Physics-based model mobility map



NRMM mobility map



Concluding Remarks

- For the first time, a high-fidelity physics-based simulation to predict vehicle mobility measures over large terrain maps was presented. Modeling approach based on:
  - Seamless integration of MBD for modeling the vehicle and DEM for modeling cohesive soils into one solver.
  - An HPC DOE procedure.
  - A moving terrain patch strategy.
- This general approach is proposed to replace the current practice of NRMM.
- Future work will focus on:
  - Expanding the DOE procedure to include additional terrain and soil properties.
  - Experimental calibration and validation for the physics-based model.